# Final Report

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# Improvements in Representations of Cloud Microphysics for BBHRP and Models using Data Collected during M-PACE and TWP-ICE

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In our research we proposed to use data collected during the 2004 Mixed-Phase Arctic Cloud Experiment (MPACE) and the 2006 Tropical Warm Pool International Cloud Experiment (TWP-ICE) to improve retrievals of ice and mixed-phase clouds, to improve our understanding of how cloud and radiative processes affect cloud life cycles, and to develop and test methods for using ARM data more effectively in model. In particular, we proposed to:

1) use MPACE in-situ data to determine how liquid water fraction and cloud ice and liquid effective radius ($r_{ei}$ and $r_{ew}$) vary with temperature, normalized cloud altitude and other variables for Arctic mixed-phase clouds, and to use these data to evaluate the performance of model parameterization schemes and remote sensing retrieval algorithms;
2) calculate $r_{ei}$ and size/shape distributions using TWP-ICE in-situ data, investigate their dependence on cirrus type (oceanic or continental anvils or cirrus not directly traced to convection), and develop and test representations for MICROBASE;
3) conduct fundamental research enhancing our understanding of cloud/radiative interactions, concentrating on effects of small crystals and particle shapes and sizes on radiation; and
4) improve representations of microphysical processes for models (fall-out, effective density, mean scattering properties, $r_{ei}$ and $r_{ew}$) and provide them to ARM PIs.

In the course of our research, we made substantial progress on all four goals as explained below.

## 1) Use of M-PACE in-situ data to improve representations of cloud properties

For objective 1), we characterized vertical profiles of arctic mixed-phase clouds measured during M-PACE by the University of North Dakota Citation in both single and multiple layers during spiral ascents and descents over Barrow and Oliktok Point and ramped ascents and descents in between. With clouds defined as locations where the total water content (TWC) was greater than 0.001 g m$^{-3}$, there were a total of 513 30-s averaged SDs in single layer clouds, of which 71% were mixed-phase, 23% ice-phase and 6% liquid-phase, where phase was identified using information from a combination of in-situ probes (McFarquhar et al. 2007b). The mixed-phase parcels were dominated by contributions from liquid drops, with the liquid mass fraction $f_l$ averaging 0.89±0.18 with 75% of cases having $f_l > 0.9$. For single layer clouds, $f_l$ increased with normalized cloud altitude $z_n$, defined as linearly increasing from 0 at cloud base to 1 at cloud top with $f_l$ averaging

0.96±0.13 near $z_n$=1 and 0.70±0.30 near $z_n$=0 (McFarquhar et al. 2007b). The $r_{ew}$ increased with $z_n$, from an average of 6.9±1.8 um near $z_n$=0 to 11.4±2.4 um near $z_n$=1, whereas $r_{ei}$ (25.2±3.9 um) was nearly independent of $z_n$. The averaged cloud droplet number concentration ($N_w$) and concentrations of ice crystals ($N_i$) with maximum dimensions D greater than 53 um were 43.6±30.5x$10^3$ $L^{-1}$ and 2.8±6.9 $L^{-1}$, respectively, and nearly independent of $z_n$. In contrast to past measurements combined from many geographical locations where $f_l$ increased with temperature, $f_l$ decreased from -12 to -3ºC as clouds typically consisted of a liquid topped layer above precipitating ice. Similar analysis of stratus that occur in multiple layers between 5 and 8 October 2004 showed that ice crystals contributed more to the mass contents in multi-layer clouds, with ice-phase noted 55% of the time and mixed-phase clouds and liquid-phase noted 29% and 17% of the time respectively (Zhang et al. 2008). Further, ice made greater contributions to the total mass of the mixed-phase clouds for the multi-layer stratus. A one-dimensional column model showed that the seeding of lower cloud layers from ice crystals precipitating from upper layers could explain many of the differences between multi-layer and single-layer stratus.

The biggest impact of our M-PACE analysis has been through its use by the modeling community both inside and outside of ARM for evaluating large eddy simulation (LES) models, cloud resolving models (CRMs) and general circulation models (GCMs), namely the work proposed in our objective 4. These studies, in which we have been active collaborators (we are co-authors on 7 modeling papers) have contributed to our fundamental understanding of microphysical processes in mixed-phase clouds, the third objective of our proposed work. For example, some of these studies showed that the formation of ice nuclei from drop evaporation residuals and drop freezing during evaporation cab be invoked to explain why ice crystal concentrations are greater than ice nuclei concentrations (Fridlind et al. 2007), that the Bergeron-Findeisen process mainly explains the glaciation of supercooled clouds (Sednev et al. 2008), that the response of mixed-phase arctic clouds to increased aerosol concentrations depends in part on the underlying surface conditions (Morrison et al. 2008a), that the representation of microphysics can impact the longevity and microphysical properties of mixed-phase clouds but not cause the difference in single-layer and multiple-layer clouds (Luo et al. 2008a, 2008b), and that more detailed representation of microphysical processes generally gives model simulations more consistent with observations (Klein et al. 2008; Morrison et al. 2008). We have also collaborated on studies that showed ice nuclei concentrations were in good agreement with cloud ice number concentrations of cloud particles larger than 125 μm for temperatures less than -10 ˚C (Preni et al. 2008) and that investigated the relationship between the characteristics of the mixed-phase arctic clouds and vertical motions (Shupe et al. 2008).

The M-PACE data were also used to determine the correlation between the IWC and the effective particle size (Liou et al. 2008). Using the correlation results, simulations from the UCLA GCM showed substantial regional deviations in the outgoing longwave radiative forcing and precipitation patterns from assuming a constant effective diameter, and hence are significant for future simulations of climate.

We have also completed additional analysis that we are currently under the process of preparing for publication. Many of these papers are part of the doctoral dissertation of Dr. Gong Zhang which is expected to be completed in March 2010. In Zhang et al. (2010) we are contrasting the microphysical properties of the mixed-phase clouds observed from Oct 5 to Oct 8 during M-PACE, when the artic stratus mainly occurred in a varying number of multiple layers against those properties observed from Oct 9 to Oct 12 when the mixed-phase clouds were observed to occur in a single vertically continuous layer. The comparisons show that supercooled water droplets contributed greater fractions to the total mass for the single-layer stratus compared to the multi-layer stratus, where there were greater contributions from ice crystals.

**2) Use of TWP-ICE data to improve representations of cloud microphysics**

For objective 2, we used TWP-ICE data to quantify the contributions of small ice crystals (with maximum dimension D < 50 μm) to the mass and radiative properties of cirrus (McFarquhar et al. 2007a). Quantifying the importance of small ice crystals has been a controversial and unsolved problem in cloud microphysics for the last 20 years, yet this knowledge is critically needed to quantify cirrus effects on longwave and shortwave radiation, and hence to better represent cloud feedbacks in GCMs and improve predictions of climate change. Prior studies had suggested that the shattering of large ice crystals on protruding components of the forward scattering probes used to measured small crystals into several hundred smaller ones suggested that observations of large concentrations of small ice crystals were artifacts (Field et al. 2003; Korolev and Isaac 2005). During TWP-ICE, we measured ice crystals with 3 μm < D < 50 μm in aged cirrus and fresh anvils using a Cloud and Aerosol Spectrometer (CAS) with a protruding shroud and inlet and using a Cloud Droplet Probe (CDP) without protruding components. The CAS/CDP ratio of the number concentrations of droplets with 3 < D < 50 μm, $N_{3-50}$, averaged 0.98±0.69 in liquid clouds and 91±127 in ice clouds. The CAS/CDP $N_{3-50}$ ratio had a correlation coefficient of 0.387 with the concentration of particles with D > 100 μm measured by a Cloud Imaging Probe, highly suggesting ice crystals were shattering or bouncing on the CAS inlet or shroud enhancing $N_{>3-50,CAS}$. We also showed that $N_{3-50,CAS}$ measured by a CAS without an airflow shroud during the Costa Rica Aura Validation Experiment were an order of magnitude less during TWP-ICE. This, and calculations of the maximum shattering based on the inlet and shroud sizes, showed that the airflow shroud used during TWP-ICE was responsible for much of the shattering or bouncing. To illustrate the importance of this shattering, we showed that ice crystals with 3 < D < 50 μm contributed 98%, 75% and 50% to the total number concentration (N), projected area ($A_c$), and IWC on average as estimated from the CAS/CIP SDs, yet only 63%, 32% and 20% when estimated using the CDP/CIP SDs. The differences are substantial as N could be overestimated by 300%, extinction by 106% and IWC by 49% from shattering or bouncing explains the discrepancies. Thus, model parameterizations based on data from probes with protruding shrouds and inlets may artificially enhance small ice crystal concentrations and in turn lead to overestimates of shortwave reflection by cirrus and errors in estimates of cloud radiative forcing.

To illustrate the importance of this finding, we collaborated with David Mitchell in his simulations of the NCAR Community Climate Model (CAM-3) that used different assumptions about small ice crystal concentrations smaller than the differences quoted above. This work again contributed to our objective 4. We (Mitchell et al. 2008) showed 12% differences in cloud ice amount and 5.5 % in cirrus cloud coverage globally resulted, corresponding to a net cloud forcing of -5 W $m^{-2}$ in the Tropics and differences in upper troposphere temperatures of over 3 ºC.

We also collaborated on a number of other studies using the TWP-ICE data. We collaborated with Alain Protat of the Bureau of Meteorology to derive best estimates of the bulk microphysical properties (ice water content, visible extinction, effective radius, and total concentration) for 3 case studies of tropical ice clouds sampled during TWP-ICE. Two cases were aged cirrus clouds produced by deep convection (the 27/01 and 29/01 cases), and the third (02/02) a fresh anvil produced by deep convective activity over the Tiwi Islands. As in Um and McFarquhar

(2009), we showed that the fresh anvil was associated with the more frequent occurrences of plates, columns, and aggregates of plates, whereas the aged anvil had the more frequent occurrence of pristine crystals such as bullet rosettes. Quasi-spherical particles dominated the smaller particles with maximum dimensions less than 50 micrometers for both cases. A simple methodology to minimize errors associated with the density (ρ) –D and projected area (A) – D assumptions in bulk microphysics calculation using the frequency of occurrence of each particle habit derived from the CPI data and prescribed ρ – D and A – D relationships from the literature was introduced and produced IWC estimates more consistent with bulk measures from a Counterflow Spectrometer and Impactor (CSI) probe than those obtained from the use of ρ – D and A – D relationships for single habits. This study also examined the implications of these findings for radar-lidar retrieval evaluation.

In another study (Barnard et al. 2008) we used the vertical profiles of the ice particle size distributions to estimate cloud optical depths that were compared against those derived from an algorithm using data from shortwave broadband irradiances. Good agreement was found between that from the size distributions and the remote sensing algorithms.

The TWP-ICE data also played a central role in the doctoral dissertation of Dr. Junshik Um which was completed in 2009. Several studies based on his thesis are currently under preparation for publication. Dr. Um developed a quasi-automatic habit classification scheme using the ice crystal images measured by the CPI during TWP-ICE and showed that small quasi-spheres dominated the contributions from all ice crystal sizes for all flights during TWP-ICE. However, he showed that the areal fraction from crystals with maximum dimensions (D) > 200 μm from bullet rosettes and their aggregates was 48% and 60% for cirrus measured on 27 and 29 January 2006, but only 7% for those on 2 February, whereas the fraction of aggregates of plates was 46% for 2 February and only 7% and 1% for 27 and 29 January. The difference in ice crystal habits sampled on the different days is likely associated with the difference between fresh anvil cirrus on 2 February and aged cirrus bands on 27 and 29 January. These differences have important implications for both the development and evaluation of remote sensing retrievals, as well as for the calculation of the shortwave and longwave radiative forcing of cirrus (see discussion of these implications in Section 3 below). In other work, Dr. Um used the TWP-ICE data to develop an incomplete gamma fitting technique developed by our group (McFarquhar and Freer 2010) that gives more accurate estimates of the intercept ($N_0$), slope ($\lambda$) and shape ($\mu$) of gamma functions matching observed size distributions, to calculate the differences in shape and size distributions and bulk microphysical parameters between fresh anvils and aged cirrus (Um et al. 2010), and to determine how the microphysical properties of anvils varied according to convective strength, and distance and time away from the location of peak convective activity as determined from C-POL data, using data from both the Egrett and Scaled Composites Proteus collected during TWP-ICE. This issue is being further examined in our new ARM proposal.

### 3) Fundamental Research on Cloud/Radiative Interactions

Research in this area has explored how different shapes of aggregate ice crystals affect the scattering and absorption of solar radiation. First, ice crystals imaged by the CPI during the 2000 Cloud IOP over the SGP were used to develop relationships between how the length and width of bullets, the fundamental components of the aggregates of bullet rosettes observed during several flights of the UND Citation, were related. Then, an idealized model of aggregates of bullet rosettes was derived by attaching six bullet rosettes, each of which was composed of 6 bullets of the same size but each of which had different-sized bullets from the other bulleted rosettes, together randomly without overlap. Using a geometric ray-tracing method, the phase function, asymmetry parameter and single-scattering Albedo of the aggregates and of the component bullets and bullet rosettes were calculated at visible and near-infrared wavelengths. It was found that as the aspect ratio of the component bullets increased, the forward scattering increased by up to 1.3% and the lateral and backward scattering decreased by up to 8.9% and 10.2% respectively at non-absorbing wavelengths. For longer wavelengths, light absorption decreased the rate at which these scatterings changed with aspect ratio (Um and McFarquhar 2007). The implications of these shapes for remote sensing studies were shown, with the difference in the bidirectional reflectance distribution function for the aggregates and a bullet rosette differing by up to 107% at moderately absorbing wavelengths and by up to 35% and 28% at non-absorbing and strongly absorbing wavelengths.

During TWP-ICE, aggregates of both bullet rosettes and chain aggregates of plates were observed using a Cloud Particle Imager (CPI). Although we developed a good description of the single-scattering properties of aggregates of bullet rosettes in our previous work, there had yet to be a good description of the scattering properties of aggregates of plates developed. Because such properties are used for both development of remote sensing retrieval algorithms and for development of bulk single-scattering parameterizations for large-scale models, and because aggregates of plates have also been observed during previous field campaigns (i.e., TEFLUN-B, CRYSTAL-FACE, and EMERALD-II) we determined the scattering properties of such aggregates and their dependence on the crystal morphology, assuming that an aggregate consisted of a cluster of 2 or more plates attached together. The single-scattering properties (i.e., asymmetry parameter g and scattering phase function P11) for idealized models describing these aggregates were calculated using a ray-tracing code at solar wavelength. The CPI images were used to determine the sizes and shapes of 7 representative plates, and the manner in which these plates were combined together to make the aggregates. We found that as the plate size increased, g increased. However, the increase of g was not due to the increase of size but rather due to the accompanying decrease of aspect ratio. We also found that g typically decreased as the number of attached plates increased, but that the rate of decrease was not linear. In an attempt to explain this non-linearity a new parameter, the *aggregation index (AI)* was introduced. The AI is defined as the distances between plates divided by the distances between plates when the plates lay on a straight line. It was shown that g could be represented as a function of AI so that the non-linear decrease of g could be explained by the morphology of the aggregates. We finally found that the g value of the aggregates was reduced and the halos in the scattering phase function disappeared when surface roughness was added.

Based on the shapes of ice analogues grown in laboratory experiments, we also developed a new model (budding bucky ball, 3B) for the shape of small ice crystals. The 3B scatters more light in the lateral and backward direction, and less in the forward direction compared with other existing models currently used to describe small crystal shape (i.e., Gaussian random sphere and droxtal). The combination of the reduction in the forward scattering and enhancement in the lateral and backward scattering caused 11% and 9% decreases in g for the 3B compared with the Gaussian random sphere and droxtal respectively. Using the TWP-ICE observations, we then quantified the impacts of the variations in small ice crystal shapes on the bulk scattering properties of tropical cirrus. The calculated mean g for the fresh anvil (2 February) was larger than that for the cirrus bands of varying ages (27 and 29 January) at the coldest and warmest cirrus temperatures where the fractional contributions of small ice crystals to total cross sectional area were small. Future work will explore the implications of this study for remote sensing retrievals, model parameterization development and cirrus radiative forcing.

Finally, the CPI images were also used to investigate how the shapes of small ice crystals measured during TWP-ICE differed from those measured during previous mid-latitude field campaigns (Nousiainen et al. 2010). The TWP-ICE images were used to compile a statistical autocovariance function of radius for the ensemble of particles measured, and then used in conjunction with the Gaussian random sphere geometry to generate three-dimensional model ice particles. The single-scattering properties at visible wavelengths were computed using the ray-optics approximation. The comparison between tropical and mid-latitude properties revealed that the tropical quasi-spherical ice crystals were closer to spherical than their midlatitude counterparts, and as a consequence, their asymmetry parameters were larger. The impact of internal scatterers, such as air bubbles, on scattering was also determined. It was found that the internal scatterers had a potentially large impact on the single-scattering properties, yet no data were available to estimate realistic values for the internal scatterers to assess their likely impact in nature.

**4) Improved Representation of Microphysical Processes in Models**

We have collaborated with a number of modelers inside and outside of the ARM program with the use of the MPACE and TWP-ICE data on the development of model parameterizations and on the evaluation of modeled fields and the representation of microphysical processes in models. This has resulted in the submission, publication and preparation of many different studies on both M-PACE and TWP-ICE as discussed above (Fridlind et al. 2007; Klein et al. 2007; Luo et al. 2007a; Luo et al. 2007b; Mitchell et al. 2007; Morrison et al. 2007; Sednev et al. 2007). These studies have addressed questions like the source of ice crystals in mixed-phase clouds, reasons for the persistence off mixed-phase clouds, the impacts of small crystals on the simulation of climate, the performance of single-moment and double-moment microphysical parameterization schemes in mesoscale models, and that the sensitivity of Arctic mixed-phase clouds (and their radiative properties) to changes in cloud condensation and ice nucleus concentrations depends in part on the underlying surface conditions.

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